QA: N/A

Civilian Radioactive Waste Management System
Management & Operating Contractor

Natural Analogue Synthesis Report

TDR-NBS-GS-000027 REV00 ICN 02

May 2002

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CHANGE HISTORY

Revision Number	Interim Change No.	Effective Date	Description of Change
00		02/15/2002	Initial Issue.
00	01	04/15/2002	Interim change to address comments per AP-7.5Q, Submittal, Review, and Acceptance of Deliverables. Text modified for grammar. Changes indicated by sidebar in margin.
00	02	05/01/2002	Interim change to Table 1-1, KTI Agreements and to correct typographical errors. Text modified on pp. 1T-1, 3-1, 4-1, 6-2, 7-2, 8-1, 10-1, 11-1, 11-5, 11-18, 14-1. Changes indicated by sidebars in margin; on pages modified for ICN 02, only those changes associated with ICN 02 are noted by sidebars.

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ACRONYMS AND ABBREVIATIONS

1-D	one-dimensional, one dimension
2-D	two-dimensional, two dimensions
3-D	three-dimensional, three dimensions
ACC	accession number
AMR	Analysis/Model Report
AP	Administrative Procedure
BDCF	Biosphere Dose Conversion Factor
BP	Before Present
BSC	Bechtel SAIC Company, LLC
CEC	Cation Exchange Capacity
CFR	Code of Federal Regulations
ChNNP	Chernobyl Nuclear Power Plant
CRWMS	Civilian Radioactive Waste Management System
DCM	dual-continuum model
DCPT	dual-continuum particle tracker
DIC	dissolved inorganic carbon
DIRS	Document Input Reference System
DOE	U.S. Department of Energy
DST	Drift Scale Test
DTN	Data Tracking Number
EBS	Engineered Barrier System
ECRB	Enhanced Characterization of Repository Block
EHPA	Di (2-Ethylhexyl) Phosphoric Acid
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
ESF	Exploratory Studies Facility
FEHM	Finite Element Heat and Mass Transfer
FEP	Features, Events, and Processes
FY	Fiscal Year
GMWL	Global Meteoric Water Line
IAEA	International Atomic Energy Agency
IFC	International Formulation Committee
INEEL	Idaho National Engineering and Environmental Laboratory
ISM	Integrated Site Model
ITN	Input Tracking Number
KTI	Key Technical Issue

ACRONYMS AND ABBREVIATIONS (Continued)

LA	License Application
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LBT	Large Block Test
LLNL	Lawrence Livermore National Laboratory
LPIT	Large Scale Aquifer Pumping and Infiltration Test (at INEEL)
M&O	Management and Operating Contractor
N/A	not applicable
NARG	Natural Analogue Review Group
NAT	Neutron-Probe Access Tube
NEA	Nuclear Energy Agency
NKC	sodium-potassium-calcium
NRC	U.S. Nuclear Regulatory Commission
NTS	Nevada Test Site
NWTRB	Nuclear Waste Technical Review Board
OCRWM	Office of Civilian Radioactive Waste Management
PA	Performance Assessment
PGA	peak ground acceleration
PMR	Process Model Report
Q	Qualified
QA	Quality Assurance
QAP	Quality Administrative Procedure
QARD	Quality Assurance Requirements and Description
QIP	Quality Implementing Procedure
REE	rare earth elements
RPM	Rock Properties Model
RWMC	Radioactive Waste Management Complex (at INEEL)
SDA	Subsurface Disposal Area (within RWMC, at INEEL)
SEM	scanning electron microscope
S & ER	Yucca Mountain Science and Engineering Report
SHT	Single Heater Test
SN	Scientific Notebook
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SR	Site Recommendation
SRPA	Snake River Plain Aquifer

ACRONYMS AND ABBREVIATIONS (Continued)

STN	Software Tracking Number
SZ	saturated zone
TBD	to be determined
TBV	to be verified
TDMS	Technical Data Management System
TDS	total dissolved solids
TH	thermal-hydrologic
THC	thermal-hydrologic-chemical
THCM	thermal-hydrologic-chemical-mechanical
THM	thermal-hydrologic-mechanical
TIMS	thermal ionization mass spectrometry
TNT	trinitrotoluene
TOUGH	Transport Of Unsaturated Groundwater and Heat
TRU	transuranic
TSPA	Total System Performance Assessment
TSPA-SR	Total System Performance Assessment Site Recommendation
TWP	Technical Work Plan
UMTRA	Uranium Mill Tailing Remedial Action
UNE	Underground Nuclear Explosion
US	United States
USGS	United States Geological Survey
UZ	unsaturated zone
VA	Viability Assessment
WFD	waste form degradation
WP	waste package
XRD	x-ray diffraction
XRF	x-ray fluorescence
YM	Yucca Mountain
YMP	Yucca Mountain Site Characterization Project
YMSD	Yucca Mountain Site Description

ACRONYMS AND ABBREVIATIONS (Continued)

UNITS

Bq	becquerel
Ci	curie
g	gram
ka	thousand years ago
kg	kilogram
ky	thousand years
m	meter
Ma	million years ago
masl	meters above sea level
mg/L	milligrams per liter
mL/g	milliliters per gram
mm	millimeter
μmho/cm	micro-mho per centimeter
MPa	megapascal
mR/hr	millirads per hour
Mt	megaton
m.y.	million years
Pa	pascal
pCi	picocurie
rem	roentgen equivalent man (i.e., the amount that produces the same damage to humans as 1 roentgen of high-voltage x-rays)
Sv	sievert
t	ton
t/ha	tons per hectare
yr	year

MAJOR HYDROGEOLOGICAL UNITS

CFu	Crater Flat undifferentiated hydrogeologic unit
CHn	Calico Hills nonwelded hydrogeologic unit
PTn	Paintbrush Tuff nonwelded hydrogeologic unit
TCw	Tiva Canyon welded hydrogeologic unit
TSw	Topopah Spring welded hydrogeologic unit

1. INTRODUCTION

1.1 PURPOSE OF REPORT AND LIMITATIONS

The purpose of this report is to present analogue studies and literature reviews designed to provide qualitative and quantitative information to test and provide added confidence in process models abstracted for performance assessment (PA) and model predictions pertinent to PA. This report provides updates to studies presented in the *Yucca Mountain Site Description* (CRWMS M&O 2000 [151945], Section 13) and new examples gleaned from the literature, along with results of quantitative studies conducted specifically for the Yucca Mountain Site Characterization Project (YMP). The intent of the natural analogue studies was to collect corroborative evidence from analogues to demonstrate additional understanding of processes expected to occur during postclosure at a potential Yucca Mountain repository. The report focuses on key processes by providing observations and analyses of natural and anthropogenic (human-induced) systems to improve understanding and confidence in the operation of these processes under conditions similar to those that could occur in a nuclear waste repository. The process models include those that represent both engineered and natural barrier processes. A second purpose of this report is to document the various applications of natural analogues to geologic repository programs, focusing primarily on the way analogues have been used by the YMP. This report is limited to providing support for PA in a confirmatory manner and to providing corroborative inputs for process modeling activities. Section 1.7 discusses additional limitations of this report.

Key topics for this report are analogues to emplacement drift degradation, waste form degradation, waste package degradation, degradation of other materials proposed for the engineered barrier, seepage into drifts, radionuclide flow and transport in the unsaturated zone (UZ), analogues to coupled thermal-hydrologic-mechanical-chemical processes, saturated zone (SZ) transport, impact of radionuclide release on the biosphere, and potentially disruptive events. Results of these studies will be used to corroborate estimates of the magnitude and limitation of operative processes in order to build realism into conceptual and numerical process models used as a foundation for PA in the representative case of postclosure safety.

1.2 DEFINITION OF ANALOGUE

Natural analogues refer to either natural or anthropogenic systems in which processes similar to those expected to occur in a nuclear waste repository are thought to have occurred over long time periods (decades to millenia) and large spatial scales (up to tens of kilometers). Analogues provide an important temporal and spatial dimension to the understanding of processes not accessible to laboratory experiments that may take place in a nuclear waste repository and surrounding area. The use of analogy has been endorsed by the international nuclear waste community as a means of demonstrating confidence in the operation of systems, components, and processes related to nuclear waste disposal (e.g., publications of the International Atomic Energy Agency [IAEA] and the European Community's Natural Analogue Working Group). "The role of a natural analogue should … be to confirm: (a) that the process is in fact something which can or will occur in practice as well as in theory, and in nature as well as in the laboratory; (b) where, when, and under what conditions it can occur; (c) that the effects of the process are those envisaged in the model; and (d) that the magnitude of the effects in terms of scale and time are similar to those predicted for a similar set of conditions" (Chapman and Smellie 1986 [124323], p. 167).

1.3 ROLE OF NATURAL ANALOGUES IN PROCESS MODELS AND PERFORMANCE ASSESSMENT

Natural analogues may be applied in a quantitative or a qualitative manner, depending upon the purpose to which they are applied and upon the specific analogue. They can provide descriptive information about the occurrence of various processes, or they may be able to constrain the bounds of those processes. Natural analogues allow testing of the pertinence of individual processes over geologic time and space scales, assessing the relative importance of various processes, and gauging the effects of process coupling. For some processes (e.g., those that are thermally coupled), natural analogues may be the only means of providing the required understanding of long-term and large-scale behavior needed to provide scientific confidence in process models for input to total system performance assessment (TSPA). Analogue investigations may determine the conditions under which the processes occur, the effects of the processes, and the magnitude and duration of the processes.

Analogue information may also provide a body of data for testing codes and for validation of conceptual and numerical models. Natural analogue information may also be used to build confidence in databases themselves. Because natural analogues can be used to evaluate the validity of extrapolating from temporally limited field-scale experiments to longer time scales, or to add confidence when extrapolating from laboratory and intermediate-scale experiments to tests at larger spatial scales, they are uniquely suited to building confidence in process models. In this manner, they are used as a means of model validation, or confidence-building. Each of the Process Model Reports (PMRs) that support Site Recommendation (SR) includes a section on "validation" that in many cases utilizes natural analogue information.

Less commonly, natural analogues may be used to assist and support the selection of scenarios and to establish the probability of occurrence of selected scenarios. Natural analogues do not reduce uncertainty *per se*; that is, the uncertainty bounds on a given parameter value may remain unchanged. However, natural analogues can build confidence that the bounds are set appropriately. Because some uncertainties are greater in natural analogues than at the site being characterized, information from natural analogues should only be used in conjunction with other information to evaluate consistency with laboratory and field data.

Comparison of model predictions with the results of natural analogue investigations will in general only permit confirmation that the model takes into account the relevant processes in appropriate ways. Validation of a predictive model by such comparison provides reasonable assurance that the model reflects future behavior. This is the level of confidence required by 66 FR ([156671], p. 55804), which states, in §63.101(a): "Demonstrating compliance will involve the use of complex predictive models that are supported by limited data from field and laboratory tests, site-specific monitoring, and natural analogue studies that may be supplemented by prevalent expert judgment."

1.4 ROLE OF NATURAL ANALOGUES IN LICENSE APPLICATION

The National Research Council endorsed the use of natural analogues as "natural test cases, geological settings in which naturally occurring radioactive materials have been subjected to environmental forces for millions of years" (National Research Council 1990 [100061], p. 27). The Council's report indicates that natural analogues are essential for validating performance assessment models of geologic repositories over thousands or millions of years, as well as forming the basis for communicating the safety of a deep geologic repository in terms the public can understand. The Nuclear Waste Technical Review Board concurred in these recommendations (NWTRB 1990 [126162], p. xiii).

In 66 FR ([156671], p. 55804, Section 63.101(a)(2)), the Nuclear Regulatory Commission (NRC) has identified natural analogues as one way of demonstrating compliance with the reasonable expectation that postclosure performance objectives will be met. As summarized in Section 1 of this report, the NRC also specifies natural analogues as one method to provide the technical basis for models in (66 FR [156671], p. 55804).

The content requirements for the license application (66 FR [156671], p. 55798, Section 63.21(c)(15)) specify natural analogue studies as one of the measures used to support analyses and models that are used to assess performance of a geologic repository. In addition, the technical criteria for a license application (66 FR [156671], p. 55804) specify the use of natural analogue information as part of the demonstration of compliance with the performance objectives of the disposal regulations. Further, the demonstration of the concept of multiple barriers and the performance of complex engineered structures must include information from natural and archaeologic analogs (66 FR [156671], p. 55805, Section 63.102(h)). The importance of natural analogs in supporting performance assessment models is again included in the requirements for performance assessment (66 FR [156671], p. 55807, Section 63.114(g)).

Ten agreements from the DOE-NRC technical exchanges and management meetings on key technical issues (KTIs) include mention of analogues or information from analogue studies as necessary to address the agreement item. As shown in Table 1-1, two KTI agreement items are at least partially addressed by information in this report. A cross reference to this table is found in the sections of this report that could provide information related to these KTIs.

1.5 CRITERIA FOR SELECTION OF ANALOGUES USED IN MODEL VALIDATION

As pointed out by Pearcy and Murphy (1991 [157563]), the 10,000-year period required for high-level waste isolation is a difficult period to approximate with natural analogues. For instance, most ore deposits are on the order of a million to a billion years in age, whereas anthropogenic sites (i.e., human made) are generally on the order of a few thousand years or less. To be most helpful in terms of long-term processes relevant to a high-level waste repository, it would be useful to find analogues with ages on the order of 1,000 to 1 million years.

Because no single site will be a perfect analogue to all ongoing and anticipated processes at Yucca Mountain, focus is placed on identifying sites having analogous processes rather than total system analogues. Nevertheless, it is still worthwhile to attempt to match as many features and characteristics as possible when identifying suitable analogue sites. An ideal analogue site to long-term radionuclide transport at Yucca Mountain would have to satisfy the following conditions: (1) a known source term, (2) a similar set of radionuclides, (3) well-characterized with site data, (4) similar geologic conditions, (5) observable long-term conditions, (6) identifiable boundaries of the system, and (7) a clear-cut process that can be decoupled from other processes. It is most useful if the analogue has been in place for at least thousands of years, so that the results of long-term behavior are observable.

In addition to using natural analogues for long-term predictions, models must be able to explain and match the transport times and pathways from contaminated sites that provide anthropogenic analogues, such as Hanford, Washington; the Idaho National Engineering and Environmental Laboratory (INEEL); and the Nevada Test Site (NTS). Anthropogenic analogue sites are a challenge to constrain in models, because they often contain more than one contaminated source, (sometimes with poorly identified source terms), have a complex mixture of radionuclides and other contaminants, and often occur in highly heterogeneous formations.

With respect to choosing different geochemical transport analogues, Chapman and Smellie (1986 [124323], p. 168) state the following:

> The essentials to bear in mind when selecting analogues are as follows: (1) The process involved should be clear-cut. Other processes which may have been involved in the geochemical system should be identifiable and amenable to quantitative assessment as well, so that their effects can be accountable. (2) The chemical analogy should be good. It is not always possible to study the behavior of a mineral system, chemical element or isotope identical to that whose behaviour requires assessing. The limitations of this should be fully understood. (3) The magnitude of the various physicochemical parameters involved (P, T, Eh, concentration, etc.) should be determinable, preferably by independent means. (4) The boundaries of the system should be identifiable (whether it is open or closed, and consequently how much material has been involved in the process being studied). (5) The time-scale of the process must be measurable, since this factor is of the greatest signficance for a natural analogue.

Care must be taken in selection of an appropriate analogue to represent correctly the process of interest. For example, all uranium deposits are not categorically good analogues for stability of a nuclear waste repository. Uranium deposits indicate the long-term stability of some geologic environments, but some of the same ore deposits could be used to make arguments for massive transport of radioactive materials over large distances by natural processes. Care must also be exercised to exclude those analogues for which initial and/or boundary conditions are poorly known and where important data, such as the source term, are poorly constrained and may not be obtainable. A given site will usually only be analogous to some portion of a repository or to a subset of processes that will occur in a repository. Furthermore, additional processes will have occurred that are not characteristic of the repository. Therefore, choices must be made to select the processes of greatest relevance and the ability to isolate them for study. The long-term nature of analogues introduces some limitations and uncertainties, but analogues can still be used effectively if appropriate selection criteria are determined and applied.

In the early 1990s, the U.S. Department of Energy (DOE)/YMP convened a panel of international experts in natural analogues to provide guidance in selection and use of natural analogues for implementation by the YMP. The Natural Analogue Review Group (NARG) report recommended that natural analogues be process-oriented and "should address the issues resulting from the perturbation of a natural system (the geologic site) by the introduction of a technological system (the repository)" (DOE 1995 [124789], p. 2). The NARG was explicit in stating that "one should clearly discriminate such studies from those which, following the classical approach of earth sciences, are based on the comparative study of geological sites or situations. In particular, all investigations normally part of site characterization, even when considering comparisons with similar remote sites, such as (paleo)hydrology, etc., should not be considered as natural analogue studies" (DOE 1995 [124789], p. 2). The YMP has abandoned that approach and now defines analogues in a more all-encompassing sense in order to avoid the narrower definition.

1.6 SCOPE AND ORGANIZATION OF REPORT

This report considers a broad range of analogues that encompass both the engineered barriers and natural system components of a geological repository at Yucca Mountain. In each section, the conceptual basis for the process model is provided as a framework for discussion of relevant analogue studies and examples. Next, examples of analogue studies relevant to the operative processes in the conceptual models are presented. This is followed by an assessment of the applicability of the information or conclusions derived from the analogue. The current repository design approach (Section 2) and configuration of engineered barriers (Section 5) are provided as the basis against which to identify relevant analogues for those systems. Section 3 presents analogues related to drift stability. Section 4 provides qualitative corroboration of waste form degradation processes. Section 6 presents examples of analogues for waste package corrosion processes. Section 7 addresses analogues for engineered barrier components and processes. Section 8 illustrates seepage into underground openings at sites with varying degrees of analogy. Section 9 addresses unsaturated zone (UZ) flow processes, but is primarily concerned with Part I of a modeling study using INEEL data. Part I of that study describes a flow model that was calibrated using INEEL data and YMP modeling methods. The calibration parameter values were then used in Part II of the study, which is described in Section 10 in a model of radionuclide transport at INEEL. Section 10 also includes results to date of the Peña Blanca field study and literature examples of analogues related to UZ transport. Section 11 presents analogues related to coupled processes, includes an extensive literature search for geothermal analogues, and summarizes experimental work on drillcore from Yellowstone National Park. In addition, Section 11 presents the results of a field and modeling study for the Paiute Ridge coupled processes analogue site and a literature study of thermal-hydrologic-mechanical (THM) processes. Section 12 presents an analysis of uranium mill tailing data relevant to saturated zone (SZ) transport and includes literature examples from selected sites. Section 13 uses parameters measured after the Chernobyl nuclear accident to arrive at Biosphere Dose Conversion Factors (BDCFs) that can be compared to those applied in the Yucca Mountain Biosphere Process Model. Section 14 provides examples of the ways in which analogues have been used to support conceptual models for volcanism and seismic hazard assessments and process models. Finally, Section 15 discusses how the analogue information is applied, both for illustrative purposes and in performance assessments. The ways in which other countries have used analogues in performance assessment are summarized. The specific needs for analogue information requested by YMP performance assessment are listed, and each of the analogues covered in the report is mapped to its use in either conceptual model development, provision of data, or model validation. In a few cases, topics are identified that could potentially increase confidence with the use of natural analogues.

1.7 QUALITY ASSURANCE

This report provides corroborating information for the modeling of natural and engineered barrier performance at Yucca Mountain. This report was developed in accordance with AP-3.11Q, *Technical Reports*. Other applicable DOE Administrative Procedures (APs) and YMP-LBNL Quality Implementing Procedures (QIPs) are identified in the Technical Work Plan (TWP) *Natural Analogue Studies for License Application* (BSC 2001 [157535]). The Activity Evaluation in the TWP (BSC 2001 [157535], Attachment I) graded the natural analogue work as being non-Q and not subject to control under the DOE Office of Civilian Radioactive Waste Management (OCRWM) Quality Assurance Requirements and Description (QARD) (DOE 2000 [149540]). All procedures followed were current revisions at the time of implementation.

The data collected under this study is corroborative and will not be used directly by Performance Assessment (PA) for licensing. This report will be used to support PA in a confirmatory manner only. The TWP stipulates that all data generated by this work will be unqualified. However, data that have been collected have been submitted to the YMP Technical Data Management System (TDMS) in accordance with AP-SIII.3Q, *Submittal and Incorporation of Data to the Technical Data Management System*. The TWP also exempts the natural analogue work from following AP-SI.1Q, *Software Management*. Procedures that were followed during the course of the work, including AP-SIII.1Q, *Scientific Notebooks*, and AP-12.1Q, *Control of Measuring and Test Equipment and Calibration Standards* are listed on the TWP. Scientific notebooks are used to provide traceability to sample collection, data analysis, calculations, and modeling studies.

Input for this report consisted of a combination of existing information from natural analogue sites reported in the literature and data collected for the YMP. Literature data not developed by the YMP are available for review through the Technical Information Center (TIC); data collected by project personnel are available in TDMS; scientific notebooks (with relevant page numbers) used in preparation of this report are listed in Table 1-2 and are available from the Records Information System (RIS). Software referenced in this report is listed in Table 1-3. More detailed discussion of software usage is provided in relevant scientific notebooks. Finally, this document was developed to meet the deliverable criteria listed in Section 5 of the TWP (BSC 2001 [157535]).

Table 1-1. KTI Agreements Addressed in This Report

Agreement Number	Text of Agreement	Section of This Report
KIA0204	Document that the ASHPLUME model, as used in the DOE performance assessment, has been compared with an analogue igneous system. (Eruptive AC-2). DOE agreed and will deliver calculation CAL-WIS-MD-000011 that will document a comparison of the ASHPLUME code results to observed data from the 1995 Cerro Negro eruption. This will be available to the NRC in January 2001. DOE will consider Cerro Negro as an analogue and document that in Eruptive Processes AMR (ANL-MGR-GS-000002). This will be available to the NRC in FY2002 (Eruptive AC-2).	14.3
KUZ0407 [1]	Provide documentation of the results obtained from the Natural Analogues modeling study. The study was to apply conceptual models and numerical approaches developed from Yucca Mountain to natural analogue sites with observations of seepage into drifts, drift stability, radionuclide transport, geothermal effects, and preservation of artifacts. DOE will provide documentation of the results obtained from the Natural Analogues modeling study. The study was to apply conceptual models and numerical approaches developed from Yucca Mountain to natural analogue sites with observations of seepage into drifts, drift stability, radionuclide transport, geothermal effects, and preservation of artifacts. This will be documented in the Natural Analogues for the Unsaturated Zone AMR (ANL-NBS-HS-000007) expected to be available to NRC FY 2002.	3.2–3.4, 6.2, 8.2–8.4, 10.3–10.5, 11.2–11.5

[1] The Natural Analogue Synthesis Report replaces the AMR in the provision of documentation stated in KUZ 0407

Table 1-2. Scientific Notebooks

LBNL Scientific Notebook ID	YMP M&O Scientific Notebook ID	Responsible Individual	Page Numbers	Citation
YMP-LBNL-AMS-NA-1	SN-LBNL-SCI-108-V1	Simmons, A.	83–87, 124–127, 139–144	Simmons 2002 [157544]
YMP-LBNL-AMS-NA-2	SN-LBNL-SCI-108-V2	Simmons, A.	6–23	Simmons 2002 [157578]
YMP-LBNL-AMS-NA-AU-2	SN-LBNL-SCI-186-V1	Unger, A.	55–63	Simmons 2002 [157578]
YMP-LBNL-DSM-ELS PD-2	SN-LBNL-SCI-190-V2	Dobson, P.	79–80	Simmons 2002 [157578]
YMP-LBNL-AMS-NA PD-1B	SN-LBNL-SCI-185-V1	Dobson, P.	7-1	Simmons 2002 [157578]
YMP-LBNL-AMS-NA PD-photos	SN-LBNL-SCI-185-V1	Dobson, P.	Roll 17 Images 2 and 4	Simmons 2002 [157578]
N/A	SN-LANL-SCI-237-V1	Murrell, M.	16	Simmons 2002 [157578]
N/A	SN-LANL-SCI-215-V1	Lichtner, P.	6–32, 56–59, 63, 69–76, 89–94, 100–104, 107, 110–112, 117–118, 128, 130–131	Simmons 2002 [157578]
N/A	SN-LANL-SCI-234-V1	Lichtner, P.	16, 20, 22–24, 26–33, 61–68, 75–76, 83, 88–90	Simmons 2002 [157578]

Table 1-3. Software Codes Referenced in Text

Software Name	Version Number	Software Tracking Number	Software Reference by Section
ASHPLUME	V 1.4LV	10022-1.4LV-00	14.3
ASHPLUME	V 2.0	10022-2.0-00	14.3
CXTFIT	V 2.1	N/A [2]	10.3.2.1, 11.4.7.1
DRKBA	V 3.3	10071-3.3-00	14.4
EQ3/6	V 7.2b	UCRL-MA-110662	11.2.12.1, 11.3.5
FEHM	2.0	10031-2.00-00	10.3.1, 10.3.6.1, 10.3.6.3, 10.3.6.5
FLOTRAN	1.0	N/A	10.3.1, 10.3.6.1, 10.3.6.3, 10.3.6.4, 11.4.7, 11.4.7.1, 11.4.7.2,
iTOUGH2[1]	V 4.0	N/A	9.3.3, 9.3.5, 9.3.6, 9.3.7, 9.5
Mathematica	V 4.1	N/A	10.3.6.4
TOUGH2	V 1.4	10007-1.4-01	11.3.5
TOUGHREACT	V 2.2	10154-2.2-00	11.3.5
TOUGHREACT	V 2.3	10396-2.3-00	11.3.5
UDEC	V 2.0	B00000000-01717-1200-30004	14.4

NOTE: [1] iTOUGH2 with EOS9 and EOS7r modules

[2] N/A signifies that the code is unqualified and it is currently not tracked by the Software Configuration Management System.

2. REPOSITORY DESIGN SELECTION FOR SITE RECOMMENDATION AND RELATION TO APPLICABLE ANALOGUES

2.1 INTRODUCTION

Studies of natural and anthropogenic systems can improve understanding and confidence in the variables affecting the evaluation and operation of a selected repository design. The selection of appropriate analogues to build confidence in repository design parameters should focus on the variables affecting operational parameters rather than on a specific design for a potential Yucca Mountain repository. The current design approach is flexible in that a wide range of thermal operating modes is being examined. The flexible design approach is presented in Section 2.2. The range of potential thermal operating modes is described on the basis of three evaluated scenarios in Section 2.3, while Section 2.4 presents design methods by which the thermal goals can be achieved. Section 2.5 provides a basis for evaluating analogues to repository materials and processes that are discussed in subsequent chapters.

2.2 FLEXIBLITY IN DESIGN

Refining the design and operating mode of the potential monitored geologic repository at Yucca Mountain has been an ongoing process since inception of the YMP. This iterative design process has been focused on improving the understanding of how design features contribute to the performance of a potential repository and to the uncertainty in that performance.

A primary design aspect has been the thermal load that will be generated by the repository. Previous design concepts have considered higher-temperature operating modes, in which the rock surrounding emplacement drifts exceeds the boiling point of water. More recently, to maintain flexibility in design, the design process has evolved to examine the effects on the repository over a wider range of thermal conditions. A flexible approach to design was introduced in the *Yucca Mountain Science and Engineering Report* (S&ER) (DOE 2001 [153849], Section 2.1.3). The design has flexible operating modes that can be adapted to accommodate a waste stream with potentially evolving thermal characteristics.

2.3 OBJECTIVES OF THERMAL OPERATING MODES

The current design concepts range from a lower-temperature operating mode to a higher-temperature operating mode. For the lower-temperature mode, the objective is to keep the waste package surface temperature below 85°C (DOE 2001 [153849], Section 2.1.2.3). In the higher-temperature mode, the wall rock of the drift is above boiling temperature but the temperature is controlled to prevent boiling fronts from coalescing in the rock pillars between the emplacement drifts. Strategies that have been considered with regard to selecting the operating mode of the repository are presented below.

2.3.1 Manage Boiling Fronts within the Rock Pillars

The higher end of the thermal operating mode, presented in the *Supplemental Science and Performance Analyses* (SSPA) (BSC 2001 [155950], Table 2-1), assumes an average waste package maximum temperature of ~160°C. This mode preserves the capability of the rock mass to drain percolation flux through the repository horizon by preventing the boiling fronts from coalescing in the rock pillars between the emplacement drifts. In this mode, the close spacing of waste packages with thermally blended spent fuel inventories achieves a relatively uniform distribution of rock temperatures along the drift, limiting potentially complex thermal-mechanical effects resulting from a varying thermal gradient along the drift axis. This operating mode would also meet a design requirement established to maintain the integrity of the waste package cladding by not exceeding a temperature of 350°C, the temperature at which the cladding loses its integrity.

2.3.2 Maintain Drift-Wall Temperatures Below Boiling

One lower-temperature objective is to keep all the rock in the repository below the boiling point of water to reduce uncertainties associated with coupled thermal-hydrologic-chemical-mechanical processes driven by the boiling of water (BSC 2001 [155950], Section 2.3.2). In the higher-temperature operating mode described in the S&ER, the rock temperatures within the first several meters outside the emplacement drifts exceed the boiling point of water for about a thousand years.

2.3.3 Reduce Uncertainty in Corrosion Rates

The lower-temperature end of the range of thermal operating modes was defined by considering the potential for reducing uncertainty in the rate of localized corrosion of Alloy 22 waste package material. At temperatures below about 85°C or relative humidity (RH) below 50 percent, the susceptibility of Alloy 22 to crevice corrosion is very low (DOE 2001 [153849], Section 2.1.5, Figure 2-a). Operating the repository so that the temperature or relative humidity is below this window of crevice corrosion susceptibility may increase confidence that corrosion will not significantly reduce waste package service life.

2.4 MANAGING THERMAL OPERATING MODES

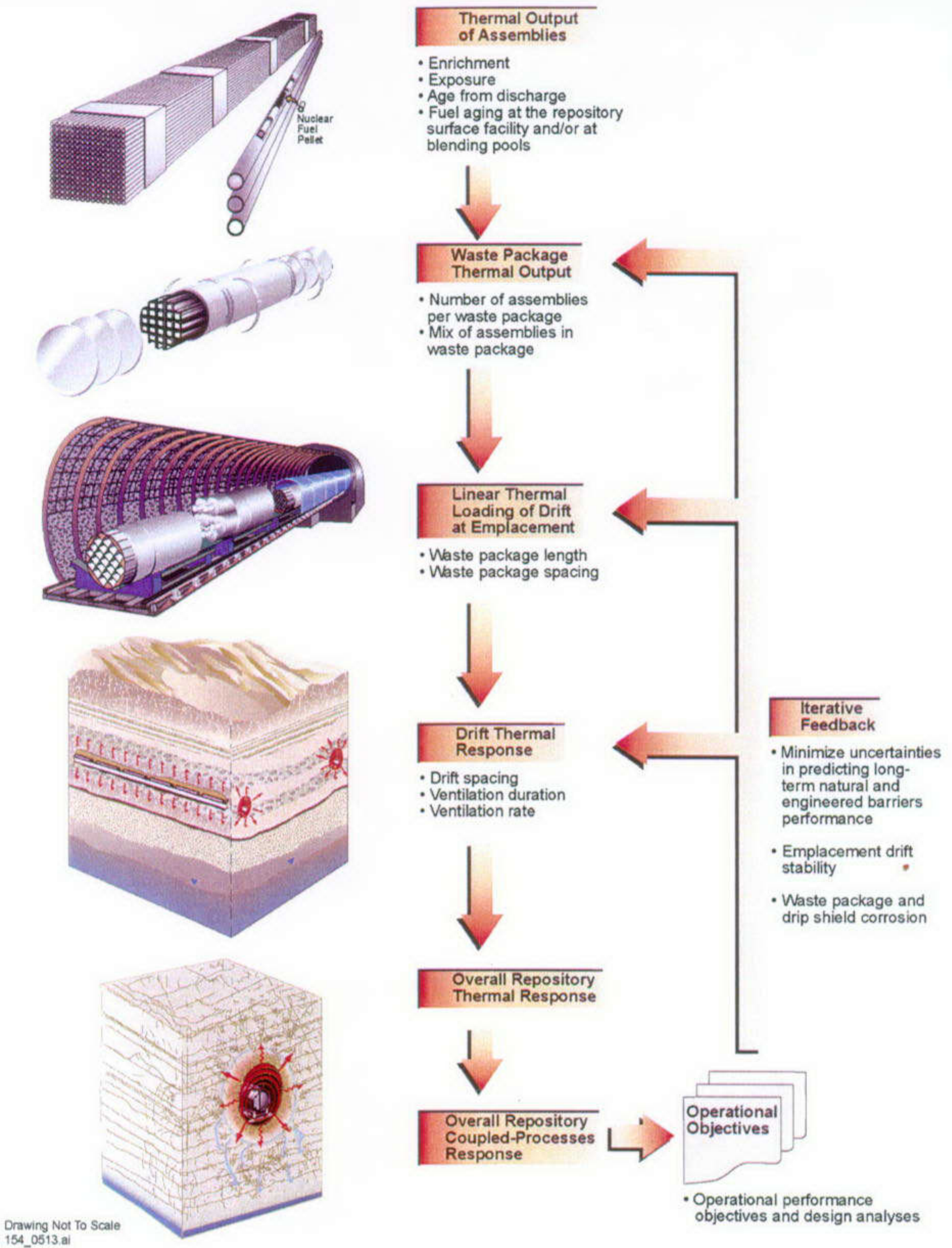
The temperature and relative humidity under which a repository would be operated for any specified underground layout can be managed either singularly or through various combinations of several operational parameters (DOE 2001 [153849], Section 2.1.4) such as by:

- Varying the thermal load resulting from the repository by managing the thermal output of the waste packages
- Managing drift ventilation prior to repository closure
- Varying the distance between waste packages in emplacement drifts.

Figure 2-1 illustrates the variables affecting the thermal performance of the repository, from waste forms to emplacement drifts.

2.5 APPLICATION TO NATURAL ANALOGUES

Because of the flexible design approach, analogues must be considered in terms of repository design variables rather than attempting to match a specific design. The important variables are temperature of drift walls, presence or absence of a boiling front, dimensions and spacing of drifts, absence of backfill, and ventilation. These variables affect drift stability (addressed in Section 3), waste package and drip shield corrosion (discussed in Sections 5 and 6, respectively), processes operative within the engineered barrier system (addressed in Section 7), and thermally coupled processes affecting the host rock at the drift and mountain scales (covered in Section 11).



Source: DOE 2001 [153849], Figure 2-8.

Figure 2-1. Variables Affecting the Thermal Performance of the Repository

3. REPOSITORY DRIFT STABILITY ANALOGUES

3.1 INTRODUCTION

Section 2 provided background information on the current flexible design for a potential repository at Yucca Mountain against which to discuss analogues for drift stability. The proposed emplacement drift diameter is 5.5 m (18 ft) (DOE 2001 [153849], Section 2.3.1.1). The ability of underground openings to remain open and stable depends on a number of variables, including: (1) rock strength; (2) the size, shape, and orientation of the opening; (3) orientation, length, and frequency of fracturing; (4) effectiveness of ground support, and (5) loading conditions. There are no exact analogues to the openings that would be created for a potential repository at Yucca Mountain, but numerous examples demonstrate that both natural and man-made underground openings can exist for thousands of years in a wide variety of geologic settings, even with minimal or no engineering. Analogue information is available for natural underground openings (Section 3.2) and man-made excavations (Section 3.3). An analogue demonstrating thermal effects on underground openings is presented in Section 3.4. Effects of ground shaking on underground openings are mentioned in Section 3.4 and discussed in more detail in Section 14. Information found in Section 3.2, 3.3, and 3.4 may help to support arguments associated with Key Technical Issue (KTI) KUZ0407 listed in Table 1-1.

3.2 NATURAL UNDERGROUND OPENINGS

Caves represent examples of natural underground openings. They are abundant, and in many cases, it can be demonstrated that they have remained open for very long spans of time. The oldest documented examples noted in this study are from the limestone formations of the Guadalupe Mountains in New Mexico. Alunite is a mineral that forms on the floor of caves. Undisturbed, uncovered alunite collected from the cave floors has been dated at 4.0–3.9 million years (m.y.) for the Big Room at Carlsbad Caverns and at 6.0 to 5.7 m.y. for the upper level of the nearby Lechuguilla Cave. Alunite from other nearby caves yields ages as old as 11.3 m.y. (Polyak et al. 1998 [156159], p. 1919). Sections of the cave floors have blocks that appear to have fallen from the ceiling; however, none of the dated caves has been closed by rockfall, demonstrating the stability of most of these openings over millions of years. Because these settings are common, they demonstrate stability for most of the openings for millions of years. Many of these openings are as large or larger than those proposed for Yucca Mountain (Figure 3-1).

The San Antonio Mountain Cave in northern New Mexico is an example of a different geologic setting in which an opening has remained open over a long period of time. This cave is a lava tube in basalt from 3.4–3.9 million years ago (Ma) (Rogers et al. 2000 [154320], pp. 89–93). The cave is more than 170 m long and generally several meters wide. In some places, the ceiling is over 12 m high. The large size of the openings combined with abundant cooling fractures has resulted in fallen blocks (generally less than ¾ m in length and width) that cover about 30% of the cave's floor. Several spots preserve a long record (up to 1 m.y.) of sedimentation, more than 400 cm thick, with no collapse (Rogers et al. 2000 [154320], Figure 5). Davis (1990 [144461], p. 338) notes that similar cave sediments in Europe date back 1.5 Ma, which suggests that long-term stability of caves is a common feature.

Most lava tubes are a few thousand to a few hundred thousand years in age. They are commonly ellipsoidal to circular in cross section and several meters in diameter. Some of the most extensive lava tubes are in the Undara region of Australia, where 190,000-year-old tubes reach 100 km in length (Undara Experience 2001 [157515]). Figure 3-2a shows the interior of a lava tube in the Undara region (with a person included in the photo for scale). Lava tubes are also common in Hawaii (Figure 3-2b) and in the Cascade Range of California, Oregon, and Washington, in lava that is modern to a few thousand years in age. Most lava tubes exhibit areas of collapse where the roof is thin, but large sections of open tunnel persist for long periods of time.

The maximum length of time that caves have stood open is usually not known, but the age dates of datable biologic or archeologic materials found in many caves indicate that the caves have remained open for extended periods of habitation without collapse. Some packrat middens found in caves are thousands to tens of thousands of years old, and Davis (1990 [144461], p. 341) reports that over 1,000 middens have been studied in caverns and rock shelters of the western United States. Stuckless (2000 [151957], p. 4-6) reports on several caves in limestone that contain paintings that have been dated at 11,000 to 32,000 years old.

Kebara Cave in Mt. Carmel, Israel, is a very large opening (26 m long and 20 m wide, with a ceiling up to 18 m high), and sediments accumulated on the floor of the cave yield ages as old as 50,000 years (Bar-Yosef et al. 1996 [157419], p. 305). Although the main portion of the cave shows no sign of collapse, a terrace in front of the cave entrance was formed by collapse sometime after 30,000 years ago (Bar-Yosef et al. 1996 [157419], p. 298). However, even this collapsed section must have stood open for more than 20,000 years, because this section was the entrance from before 50,000 until 30,000 years ago.

3.3 ANTHROPOGENIC OPENINGS

Anthropogenic, or man-made, underground openings do not provide as long a history as the natural ones, but they may provide a closer analogy to a mined geologic repository. Here too, there are abundant examples that exhibit considerable stability for hundreds to thousands of years even with minimal engineering. The oldest examples are the Neolithic flint mines of northern Europe and England. These were mined into chalk deposits in 3,000 to 4,000 B.C. At one site in England, shafts that are 6 to 14 m deep access galleries that are 4 to 24 m in length and are still open today (Crawford 1979 [157420], pp. 8–32).

Around 1,500 B.C., Egyptians began excavating tombs on the west bank of the Nile River, across from Luxor. Over 100 tombs were excavated in bedded and jointed limestone (Figure 3-3). The tombs were generally a few meters in length and width and about 2 m in height. Many have pillars that were left for support in the larger rooms. Most of the tombs have incurred some water damage to plaster and paintings on the walls and ceilings, but none seems to have suffered collapse (Simmons 2002 [157578], SN-LBNL-SCI-108-V2, p. 7).

Mining of metallic ores has produced subterranean openings in a variety of rock types and often in intensely altered or fractured rock. Unfortunately, many of the oldest examples have been mined continuously or reopened in more modern times to mine remaining lower-grade ore. The Laurion mines, about 40 km south of Athens, Greece (Figure 3-4), were first mined about 2,000 to 1,500 B.C., but were mined most actively from 600 to 300 B.C. (Shepherd 1993 [157425], p.

75). These silver and lead mines are in a gently dipping sequence of mica schists and marble, with sulfides occurring along the contacts. Shafts 1.25–1.4 m by 1.5–1.9 m were sunk up to 111 m deep (Shepherd 1993 [157425], p. 17). Underground workings were 140 km in length; tunnels averaged 1 m in width and 1.75 m in height (Shepherd 1993 [157425], pp. 17–18). Ore zones were mined out by underhand stoping, which left large cavities a couple of meters high and a few meters in diameter. Pillars of inferior ore-grade rock supported these cavities. Removal of rock from these pillars was punishable by death (Shepherd 1993 [157425], p. 25).

Bronze-age mining of metal also occurred at the Great Orme Copper Mine in Wales. Charcoal recovered from the early workings dates at 1,000 to 2,000 B.C. In 1849, miners broke into a cavern nearly 40 m long, which contained stone hammers, most likely from the Bronze Age. The cavern, mined into limestone, had stood open for nearly 4,000 years (Llandudno Museum 1998 [157526]).

Underground mining was common during the Roman Empire, and the size and state of preservation of the mines not destroyed by subsequent mining are fairly similar. Shepherd (1993 [157425]) and Davies (1935 [157421]) present locations and descriptions for most of these mines. In addition to mining for metals, the Romans created large tunnels to transport water. For instance, the aqueduct at Tresmines, Portugal, is 60 m wide, 80 m high and 480 m long; at Corta das Coras, the tunnel is 100 m wide, 100 m high, and 350 m long (Shepherd 1993 [157425], p. 17).

Buddhist monks carved temples into caves in the fractured Deccan basalts of west-central India, from approximately the second century B.C. until the tenth century A.D., with most excavated in the late fifth or early sixth century A.D. (Behl 1998 [156213], pp. 27, 39). There are 31 caves at Ajanta, India, carved along a 550 m long, horseshoe-shaped gorge of the Waghora River. Each temple originally had steps carved into the rock leading up to it, but only Cave #16 still has a vestige of steps. The monsoonal climate has destroyed the exterior stone structures exposed to the elements, but subterranean openings have been well preserved in spite of the climatic effects. Similar Buddhist caves, from the sixth through the tenth centuries A.D., are preserved at Ellora and from the ninth century A.D. (Jain caves) at Sittanavasal, India (Behl 1998 [156213], p. 39).

The cross-sectional dimensions of most of the temples at Ajanta are larger than those proposed for a mined geologic repository. For example, Cave #10 is 30.5 m × 12.2 m. Cave #2 has a verandah of 14.10 m × 2.36 m, a main hall of 14.73 m × 14.5 m, and a shrine of 4.27 m × 3.35 m. Cave #16 has a verandah of 19.8 m × 3.25 m and a main hall of 22.25 m on a side with a height of 4.6 m. In spite of these large sizes, there is no reported collapse. As in the case of the Egyptian tombs, most of the Ajanta paintings appear to have suffered some water damage and vandalism (Behl 1998 [156213], pp. 234–236).

During the second through eleventh centuries A.D., the Christians of Cappadocia, Turkey, excavated underground cities and churches. One of these cities, Derinkuyu, covered approximately 4 km^2 and had an estimated 15,000 to 20,000 inhabitants (Toprak et al. 1994 [157429], p. 54) during much of the first millennium A.D. As of 1994, eight levels of ancient habitation had been discovered. Access to the underground cities was by way of narrow passageways that could be closed by rolling a 1.5 m diameter millstone across the opening

(Figure 3-5). The excavated rooms were generally several meters across and more than 10 m long.

The geology of Cappadocia (Toprak et al. 1994 [157429], pp. 8–11) is similar to that of southern Nevada (Sawyer et al. 1994 [100075]). In both regions, the late Tertiary section is composed of a thick sequence of silicic volcanic rocks. At Yucca Mountain, the host rock for the potential repository is a densely welded, quartz latite ash-flow tuff that formed about 11.6 Ma, whereas the underground cities of Cappadocia are situated in a partially welded, rhyolite ash-flow tuff that formed about 4 to 9 Ma. The difference in welding at Yucca Mountain and the underground cities of Cappadocia results in markedly different fracture density and engineering properties. Fracture density, which is a major variable contributing to underground collapse, is much lower in the underground cities. Ground support, which would be carefully engineered at Yucca Mountain, was never used in the underground cities. Thus, the fact that there has been no collapse in the underground cities of Cappadocia during the past 1,500 to 1,800 years suggests that excavations in tuff should be stable for long periods of time if undisturbed. Stability of unsupported openings would be favored in tuffs of a low degree of welding and fracturing.

Churches were excavated into the tuff north of the underground cities at Goreme, in Cappadocia, during the ninth to thirteenth centuries A.D. (Toprak et al. 1994 [157429], p. 53). All but one of these show no evidence of collapse. The exception is a collapse of a cliff face that exposes part of the inside of one church. The interior portions of the church are still in excellent condition, and their painted walls and ceilings within are well preserved except for spallation and vandalism (Stuckless 2000 [151957], p. 22).

Some of the underground openings excavated into the tuffs of Cappadocia are still used as dwellings. There are at least two other places where underground excavations are still used as dwellings. In Tunisia, 20 to 40 km south of the city of Gabes, ten underground villages, some of which date back nine centuries, are excavated in limestone (Golany 1983 [157422], pp. 5–6). The limestone is composed of poorly indurated layers approximately 2 m thick, which are easily mined out, along with better indurated layers of similar thickness. Room sizes are typically 2 to 2.5 m on a side, with flat ceilings that may have a supporting column in the center. Similarly, in northern China, thick deposits of slightly indurated loess exist, which could be easily excavated. However, its internal structure is such that loess can form vertical cliffs as much as 30 m in height. The underground dwellings accommodate more than 10 million people, who farm the land above their houses (Golany 1983 [157422], p. 13).

Although all the examples given so far either lack ground support or utilize only unmined pillars, examples do exist of wooden ground support. Around the beginning of the second century A.D., the Roman Emperor Hadrian mandated the use of wooden supports in all mines (Shepherd 1993 [157425], p. 25). Shepherd (1993 [157425], p. 26) provides a discussion of some examples, but does not comment on the stability of openings that were shored up. Tombs in China provide a different kind of example. Sixteen emperors from the Ming Dynasty (1368 to 1644 A.D.) were buried in tombs excavated in rock near Beijing. The earliest of the tombs has 32 sandalwood pillars 1.17 m in diameter; all are still intact and sturdy (Golany 1989 [157423], pp. 21–22).

3.4 UNDERGROUND OPENINGS AFFECTED BY TEMPERATURE

The foregoing descriptions show that both natural and manmade underground openings maintain stability well in an undisturbed setting. In fact, many of the examples given, as well as several mines not discussed, have probably been subjected to significant seismic shaking. Further discussion of seismic effects on underground openings is provided in Section 14.

The stability of underground openings can also be affected by temperature. An example of thermal stresses causing rockfall around rock bolts in a heated area occurred at Linwood Mining Company's limestone excavations (Simmons 2002 [157578], SN-LBNL-SCI-108-V2, pp. 7, 8). Linwood has excavated limestone adjacent to the Mississippi River downstream from Moline, Illinois, since World War I for processing in a kiln. The mine started as a surface quarrying operation, but as excavation progressed, the mine was converted to an underground room and pillar operation. The elevation of the underground workings is lower than the Mississippi River.

The company started venting the kiln exhaust underground in 1971 as part of a solution for controlling dust emissions from the kiln (Simmons 2002 [157578], SN-LBNL-SCI-108-V2, pp. 7, 8). To do this, a 96-acre portion of the mine was nominally mined with 30 ft × 30 ft pillars 21 ft high. This portion was walled off from the active workings. Exhaust from the kiln is vented to these workings at 400°F (204°C), leaving the dust behind for later collection.

The mining company adds bolts and mesh when a karstic depression is encountered, but otherwise the mine is essentially unsupported. Perhaps for this reason, steel-bar rock bolts were placed near the entry of the exhaust. After some period of venting, the rock near the exhaust vent broke out, leaving the bolts that had been emplaced in the rock, with the bottom 5 feet or so of the bolts surrounded by air. It was suggested that the surrounding rock had probably fallen out because heat was transferred up the rock bolt faster than it was transferred through the rock, which resulted in a thermal stress that caused failure for a rock with an unconfined compressive strength of 18,000 psi (~125 MPa) (Simmons 2002 [157578], SN-LBNL-SCI-108-V2, pp. 7, 8).

3.5 SUMMARY

In Section 3, numerous examples are provided of the stability of natural and man-made underground openings for millennia or longer under undisturbed conditions. However, an inherent bias is reflected in the studies because of the difficulty of determining the relative percent of openings that remain versus those that have collapsed. It is more difficult to evaluate the cause of collapse of such openings, whether by human interference or natural causes. The ability of underground openings to remain open and stable under ambient conditions depends on a number of variables, including: (1) rock strength; (2) the size, shape, and orientation of the opening; (3) orientation, length, and frequency of fracturing; and (4) effectiveness of ground support. Radiometric dating of cave floor minerals at Carlsbad Caverns and Lechuguilla Cave indicates that natural openings larger than those proposed for repository drifts at Yucca Mountain have remained open for millions of years. Collapse of the roof of an opening tends to occur where the fracture density is high and the overburden is thin, as is the case with some lava tubes. Factors that contribute to the size of a block falling are fracture spacing, which in turn depends on rock type and texture, and the size and shape of the opening.

The oldest examples of stable man-made openings are Neolithic flint mines dating from 4,000 to 3,000 B.C. However, numerous Roman mines and some aqueducts remain intact that tended to have been constructed of a similar size and now exhibit the same state of preservation. These and other examples demonstrate that both natural and man-made underground openings can exist for thousands of years in a wide variety of geologic settings, even with minimal or no engineering.

NOTE: Areas such as this have no obvious roof blocks on the floor of the cavern or holes in the ceiling from which blocks might have fallen.

Source: Simmons 2002 [157578], SN-LBNL-SCI-108-V2, p. 6.

Figure 3-1. Photograph of Fairyland in Carlsbad Caverns, New Mexico

(a)

(b)

Source: (a) Undara Experience 2001 [157515] and (b) USGS 2000 [157517]).

Figure 3-2. Photographs of (a) Lava Tube in Undara, Australia, and (b) Nahuku Lava Tube in Hawaii